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Abstract

Capacitance probes are a fast, safe and relatively inexpensive means of measuring the relative permittivity of soils, which can then be used to estimate soil water content. Initial experiments with capacitance probes used empirical calibrations between the frequency response of the instrument and soil water content. This has the disadvantage that the calibrations are instrument-dependent. A twofold calibration strategy is described in this paper; the instrument frequency is turned into relative permittivity (dielectric constant) which can then be calibrated against soil water content. This approach offers the advantages of making the second calibration, from soil permittivity to soil water content, instrument-independent and allows comparison with other dielectric methods, such as time domain reflectometry.

A physically based model, used to calibrate capacitance probes in terms of relative permittivity (ε_r) is presented. The model, which was developed from circuit analysis, predicts, successfully, the frequency response of the instrument in liquids with different relative permittivities, using only measurements in air and water. It was used successfully to calibrate 10 prototype surface capacitance insertion probes (SCIPs) and a depth capacitance probe. The findings demonstrate that the geometric properties of the instrument electrodes were an important parameter in the model, the value of which could be fixed through measurement.

The relationship between apparent soil permittivity and volumetric water content has been the subject of much research in the last 30 years. Two lines of investigation have developed, time domain reflectometry (TDR) and capacitance. Both methods claim to measure relative permittivity and should therefore be comparable. This paper demonstrates that the IH capacitance probe overestimates relative permittivity as the ionic conductivity of the medium increases. Electrically conducting ionic solutions were used to test the magnitude of this effect on the determination of relative permittivity. The response was modelled so that the relative permittivity, independent of ionic conductivity, could be determined in solutions with an electrical conductivity of up to 0.25 S m^{-1}. It was found that a solution EC of less than 0.05 S m^{-1} had little impact on the permittivity measurement.

Introduction

Two independent lines of research have developed instruments for measurement of the relative permittivity and volumetric water content of soil: time domain reflectometers and capacitance probes.

Time Domain Reflectometry (TDR) has been very successful (Hoekstra and Delaney, 1974; Topp *et al.*, 1980; Zegelin *et al.*, 1992; Roth *et al.*, 1992; Malicki *et al.*, 1996) but proves expensive if only a small number of sensors is required. The theoretical basis for measurement of permittivity by TDR is well established (Felner-Feldegg, 1969; Heimovaara, 1994) and the effect of ionic conductivity on permittivity measurement can be neglected below 0.8 S m^{-1} (Dalton, 1992).

The improvement in quality of high frequency oscillators (50–150 MHz) and their reduction in cost has led to a resurgence of interest in the use of adaptable capacitance probes for soil water measurement (Dean *et al.*, 1987; Hilhorst *et al.*, 1993; Perdok *et al.*, 1996; Eller and Denoth, 1996; Nadler and Lapid, 1996; Ould Mohamed *et al.*, 1997; Paltineanu and Starr, 1997). They were developed to meet the requirement for an inexpensive non-radioactive field instrument which could give rapid measurements. The capacitance probe is smaller, more adaptable, less bulky and much cheaper to make than TDR instrumentation. The electrode arrangement is very adaptable, making it possible to have a variety of configurations based on the same basic circuitry.

Since both techniques utilise the relationship between

relative permittivity and water content in approximately the same frequency range (Paltineanu and Starr, 1997), the two types of system should prove complementary in furthering the understanding of the dielectric properties of soils and providing a range of instrumentation with compatible calibration functions between soil permittivity and volumetric water content.

An adaptable, lightweight, high frequency capacitance sensor to measure volumetric soil water content was developed by Dean *et al.* (1987). The same basic circuitry (Dean, 1994) has been used with a number of electrode configurations to develop capacitance sensors for different applications. One of these, a surface capacitance insertion probe (SCIP), with 100 mm stainless steel electrodes, can be used both as a hand-held field probe (Robinson & Dean, 1993) or as a buried sensor which links to a logger. It is very portable and suited to the rapid acquisition of spatially distributed measurements. This information may be used, for instance, as ground truth for remotely sensed data. Once the probe has been calibrated, it removes the need for more destructive, time consuming, gravimetric sampling. A depth probe was also developed by Dean *et al.* (1987) which is inserted into the soil via a plastic access tube and was commercially available in the early 1990s. Whalley *et al.* (1992) tested a tine mounted sensor which could be drawn behind a tractor.

These capacitance sensors share a need for calibration to relate the instrument oscillation frequency to soil volumetric water content. In earlier research, field calibrations were performed between sensor frequency output and soil volumetric water content (Bell *et al.*, 1987; Whalley *et al.*, 1992; Robinson & Dean, 1993; Wu, 1998). The same approach has been used for similar capacitance probes by Tomer and Anderson (1995) and Evett and Steiner (1995). This approach has two drawbacks; calibrations are sensor-specific and they are not directly comparable with other instruments (e.g. TDR). Robinson *et al.* (1994) and Gardner *et al.* (1998) overcame these by first converting the frequency response of a SCIP to relative permittivity (ε_r) so that instrument-independent calibrations between ε_r and water content could be established and compared with TDR. Both these sets of workers used an empirical calibration between probe frequency output and relative permittivity derived from measurements in a series of organic solvents with different permittivities. This worked well, though proving time consuming, expensive and somewhat hazardous as a result of the nature of the chemicals used.

A theoretical model was developed by Dean (1994) describing the instrument frequency response to a dielectric but it has not been extensively tested. The aims of this work are: to test the model of Dean (1994) to determine if it can be used routinely to determine relative permittivity from the instrument frequency output; to simplify the calibration of capacitance sensors, avoiding the need for empirical calibrations in hazardous and expensive organic liquids by using only two measurements, one in air and one in de-mineralised water; to investigate the effect of conductivity of the medium in which the probe is embedded on the readings, and to provide a means to correct for this effect.

Soil is not a perfect dielectric because the soil solution is an electrical conductor and its conductivity is dependent on its ionic strength. In the past, the development of capacitance methods has been inhibited by the influence of ionic conductivity (Wobschall, 1978). More recently, Mead *et al.* (1995) using the EnviroSCAN (Sentek Pty Ltd, 69 King William Street, Kent Town, SA 5067, Australia) capacitance probe demonstrated that water content is overestimated in electrically conducting soil. If capacitance methods are to be successful, the impact of ionic conductivity must be understood and accounted for.

Design and theory

CAPACITANCE PROBE DESIGN

The SCIP and depth capacitance probe are illustrated in Fig. 1. The SCIP has two 100 mm stainless steel electrodes secured in a 30 mm plastic housing at the base of the probe body. The 100 mm electrodes can be shortened to 50 mm using a plastic spacer. The circuitry is contained above the electrodes inside the main body. The oscillation frequency of the instrument is displayed on an LCD at the top of the instrument. The whole instrument weighs under 1.5 kg and is housed in a robust, water resistant, plastic casing (Fig. 1). For the experiments described here, continuity was provided by using a single experimental SCIP with detachable electrodes. The 30 mm plastic electrode mounting block of this experimental SCIP was cut in half and the main body was fitted with two male connectors which could be inserted into female connectors in detachable electrodes of 50, 100 and 150 mm length with a 25 mm centre spacing. The depth probe has the same basic circuitry, but has a pair of annular electrodes situated one above the other and bonded to the inside of the probe casing (Fig. 1).

THEORY OF OPERATION

The capacitance of a pair of electrodes is a function of the permittivity of the material surrounding the electrodes and their geometric configuration:

$$C = \varepsilon_r g \varepsilon_o \quad (1)$$

where C is capacitance, ε_r is relative permittivity, g is a geometric constant and $\varepsilon_o = 8.854$ pF m^{-1} is the electric constant. The principle of operation of the probe used here is to include the capacitor in the tuned circuit of an oscillator and note the frequency of oscillation. The Clapp (Amos, 1965) oscillator circuit was chosen for its temperature stability (Dean *et al.*, 1987). The oscillation frequency (F) of a resonant circuit is given by (Kraus, 1984):

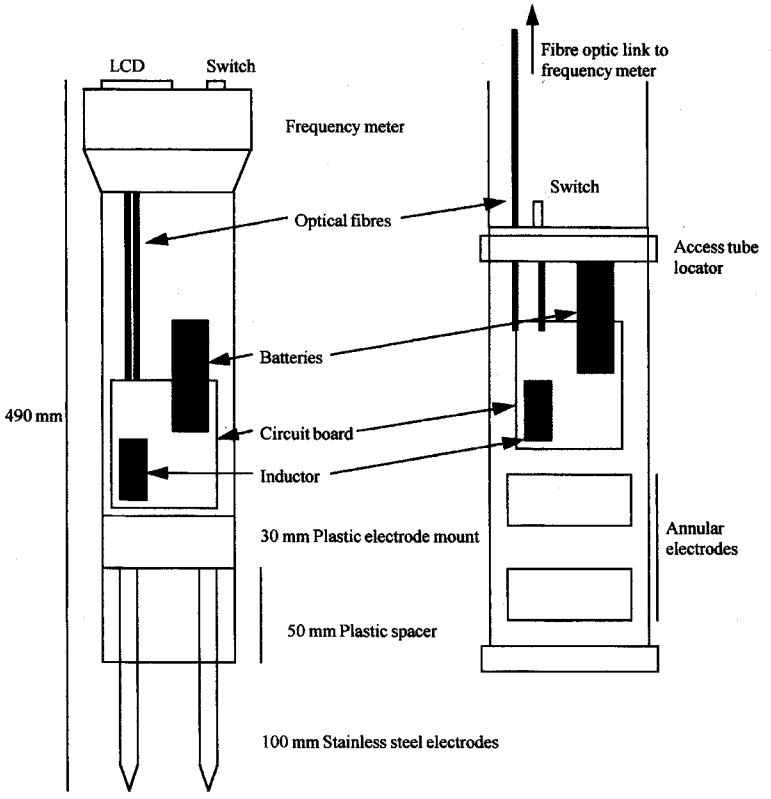

Fig. 1. *Schematic drawing of the surface capacitance insertion probe (SCIP) left, and depth probe right. The electrode and circuit configuration are highlighted.*

$$F = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

where the circuit inductance and capacitance are L and C respectively. In the instrument used here, the oscillation frequency drops from about 150 MHz in air (relative permittivity 1) to about 70 MHz in water (relative permittivity ~ 80) using 100 mm electrodes.

Oscillation frequency response model

Dean (1994) developed a model to describe the capacitance probe's circuitry and its oscillation frequency response to changes in electrode capacitance:

$$F^2 = \left(\frac{1}{(2.\pi)^2.L}\right)\left(\frac{1}{C_1 + C_2} + \frac{1}{C_3}\right) \tag{3}$$

where L is the total inductance of the circuit, composed of a component inductor and stray inductance associated with the circuit board tracks, C_1 is the electrode capacitance ($\varepsilon_r.g.\varepsilon_0$), C_2 is the stray parallel capacitance and C_3 is the circuit board capacitance. C_2 is associated with the circuit board and connections between the board and the probe. Dean (1994) demonstrated from measurements in several dielectric fluids that the probe frequency response was consistent with Eqn. (3) and that values of the various parameters were close to those expected from theoretical considerations.

To use the model for calibration of probes, values of all the parameters in Eqn. (3) are needed. L and C_2 are expected to vary between probes, whilst the other parameters should remain constant between different examples of the same design of probe (Dean, 1994). Dean (1994) found, from analysis of the circuit, that a value for the board capacitance, C_3, of 15 pF would be expected. This value accorded well with a value of 16 pF obtained by least squares fitting of the frequency readings from one probe against known values of permittivity in various dielectric liquids. The value of the geometric constant is obtained empirically through measurement, as described below.

Values of L and C_2 can be obtained from the probe's oscillation frequency in two known dielectrics, water (F_w) and air (F_a) by substitution in Eqn. (3):

$$C_2 = \frac{\sqrt{(\varepsilon_w - 1)^2.C_o^2 + \frac{2(\varepsilon_w - 1).(F_a^2 + F_w^2)}{F_a^2 - F_w^2}.C_oC_3 + C_3^2} - [(\varepsilon_w + 1).C_o + C_3]}{2} \tag{4}$$

where $C_o = \varepsilon_{air}.g.\varepsilon_o$ (i.e. the value of C_1 in air), and ε_w = relative permittivity of pure water. The inductance, L, is then:

$$L = \frac{C_o + C_2 + C_3}{4\pi^2 F_a^2.(C_o + C_2).C_3}. \quad (5)$$

Impact of ionic conductivity

If the probe is inserted into an electrically conducting medium (a lossy dielectric), the migration of ions in the high frequency field causes energy to be drawn from the circuit, damping the oscillator response. In circuit terms, the probe electrodes are analogous to a capacitor with a resistor in parallel. When the resistance across the electrodes is large, the capacitance derived from the frequency response (Eqn. (3)) is close to the true capacitance of the medium between the electrodes (C_t). As the resistance across the electrodes reduces, due to increased ionic conductivity, so the oscillator is damped and the oscillation frequency falls; the apparent electrode capacitance, C_1, thus appears greater than the true capacitance (C_t). The relative permittivity obtained from C_1 is best described as an apparent relative permittivity (κ). This will be equal to the true relative permittivity (i.e. the real part) when the resistance is high, but will increase quadratically from ε_r as the resistance drops. The effect of this conductivity can be calculated by assuming that the permittivity of the medium is composed of two parts, a real part, ε' representing the true dielectric response, and an imaginary part, ε'', due to loss mechanisms. For a medium with an ionic conductivity of σ, the imaginary part is given by $\sigma/2\pi F$, i.e.:

$$\varepsilon = \varepsilon' - j\,\sigma/2\pi F \quad (6)$$

This gives rise to a capacitance for C_1 containing a real and imaginary part, corresponding to real part, C_t, and an imaginary part, $-j/2\pi RF$ representing a resistor of value R in parallel. Both real and imaginary parts of the permittivity are related to the real and imaginary parts of C_1 by the geometric factor, g. The true capacitance, C_t, can be estimated from the apparent capacitance and resistance by substituting $C_1 = C_t - j/2\pi RF$ into Eqn. (3). The frequency of oscillation is then calculated as that which causes the imaginary part of the total impedance, $2\pi FL - (1/2\pi FC)$ to disappear. This gives:

$$C_1 = \frac{\pi C_3 RF + \sqrt{\pi^2 C_3^2 R^2 F^2 - (4\pi^2 LC_3 F^2 - 1)^2}}{2\pi RF(4\pi^2 LC_3 F^2 - 1)} - C_2 \quad (7)$$

Methods

DETERMINATION OF THE GEOMETRIC CONSTANT

Use of Eqn. (3) requires the value of the geometric constant, g, to be known to determine the shape of the oscillation frequency response curve. This needs a knowledge of C_o (= $g\varepsilon_0\varepsilon_a$). Two independent methods were compared to find which gave the best value for C_o of the 50 and 100 mm electrodes. These were direct measurement of the electrode capacitance and estimation of g from conductance measurements. Ten prototype SCIPs were then calibrated in five fluids with different permittivities. The actual permittivities were compared with those predicted by Eqn. (3) using the different geometric constants. Once the best method for measuring the geometric constant had been determined, these best values were used to calibrate the experimental probe in ten fluids with different permittivities. The value of C_o for the depth probe could be measured only using the capacitance method as the electrodes are insulated by the plastic case.

Direct measurement of electrode capacitance

An auto balancing bridge (Wayne Kerr Ltd, model B642), operating at an angular frequency of 10^4 Hz, was used to measure the capacitance of the detachable electrodes. The Wayne Kerr bridge offers capacitance measurement to 0.01 pF. The capacitance, C, is a function of the geometric factor and the relative permittivity ε_r of the medium surrounding the electrodes (Eqn. (1)).

The electrodes of the experimental probe were encased in a delrin block and a capacitance measurement made. If the electrodes are envisaged as two capacitors in parallel, the capacitance for the 30 mm delrin covered section can be determined by subtraction from the capacitance of the full 130 mm of electrode encased in delrin. Hence, the electrode capacitance in air was found by subtraction of the capacitance of the electrodes mounted in delrin from the capacitance of the delrin mounting section. The measurement was repeated for the three electrode lengths. The bridge method was also used to obtain the capacitance of the annular electrodes in the depth probe. This was much simpler as a measurement in air was all that was required to determine C_o.

Conductance vs electrical conductivity

Aqueous ionic solutions are electrically conducting due to actual charge transport. This can be expressed as a resistance (R) or conductivity:

$$\frac{1}{R} = \sigma.g \quad (8)$$

The geometric constant, g, is the same geometric constant that is applied to determining capacitance in Eqn. (1) and is an intrinsic property of the electrodes. By plotting $1/R$ *vs* σ, g can be obtained from the slope of the line passing through the origin.

The detached electrodes were immersed in water and then progressively more conducting solutions of potassium chloride. The resistance across them was measured by bridge and time domain reflectometer. The experiment began with approximately 1 litre of de-ionised water. Electrical conductivity (EC) and temperature were mea-

sured first using a Jenway EC meter with platinum electrodes. The meter compensates the readings to a standard temperature of 25 °C. Both the temperature and EC measurements were checked periodically against an independent EC meter.

The same Wayne Kerr bridge was used to measure the resistance across the stainless steel electrodes. Resistance was then measured a second time using a TDR (Tektronix model 1502C) connected to the same electrodes. Use of the TDR to measure resistance in this way is described by Dalton *et al.* (1984), Topp *et al.* (1988), Dalton (1992) and Heimovaara (1994). Measurements were taken covering a range from 0 to 0.2 S m^{-1}. The results from the resistance measurements were temperature corrected to 25 °C. This method could be applied only to the SCIPs, as the plastic case of the depth capacitance probe prevents meaningful low frequency resistance measurements.

CALIBRATION OF CAPACITANCE PROBES IN KNOWN DIELECTRICS

Prototype probes

Calibrations were performed for 10 prototype SCIPs. Five fluids with well defined relative permittivities were used; air (1), chloroform (4.9), acetone (21.2), glycol (38.7), and water (80.4). The liquid was placed in a 2 litre, inert plastic container. The temperature was measured and each probe inserted into the dielectric fluid and secured using an experimental clamp before the next measurement was taken. This was carried out for the 50 and 100 mm electrode lengths; the laboratory temperature was 20 °C.

Experimental probe

The experimental probe was calibrated in 10 dielectrics whose permittivities and temperature coefficients are given by Lide (1992), (air, white paraffin, hexanol, propan-2-ol, propan-1-ol, acetone, methanol, glycol, glycerol and water). These fluids were placed in 2 litre, chemical resistant, plastic containers. A pair of electrodes, mounted in a plastic block were inserted in the container lids. These dielectric filled containers were then used for all the subsequent experimentation.

The organic liquids used were all GPR grade. As they are all prone to absorbing water, precautions were taken to minimise this and hence reduce the risk of the permittivity being increased. 3-Angstrom molecular sieves were dried in an oven at 150 °C for 2 days, then cooled in a desiccator. On removal from the desiccator, 50 g of the molecular sieves were placed in each of the organic liquid containers and the dielectric liquid added. Once the liquid was in the containers, the lids were screwed in place. The containers were placed in an environment chamber (Townson & Mercer) along with the experimental probe and warmed to 25 °C. Five sets of measurements were taken over a period of a week.

Depth capacitance probe

The depth capacitance probe was calibrated using the same dielectrics and procedure as used for the prototype probes. Only a single probe was available to test the calibration method. The organic solvent was poured into a chemical proof container 0.4 m in diameter. The container had a plastic access tube in the centre, with a 55 mm outer diameter. The depth probe was situated in the access tube and a measurement was made as soon as the solvent had filled the container. The temperature of the solvent was then measured and the process repeated.

THE EFFECT OF SOLUTION IONIC CONDUCTIVITY ON OSCILLATION FREQUENCY RESPONSE

The experimental probe was used to determine whether Eqn. (7) could be used to determine the true electrode capacitance, and hence relative permittivity, in ionic solutions. Four dielectrics were used: water, 20% methanol in water mixture, 42% methanol in water and a 64% propan-2-ol in water mixture. The solvents were mixed with water and left for 24 hrs. Electrodes were inserted into a container with 1 litre of solution and the temperature, resistance across the electrodes (using the TDR) and capacitance probe frequency response were measured. Potassium chloride was added to the solution progressively to raise the conductivity. After mixing thoroughly, the electrodes were re-inserted into the solution and another set of measurements taken. This was repeated up to EC values of 0.25 S m^{-1} for water and 0.15 S m^{-1} for the propan-2-ol/water mixture. The solubility of an ionic salt increases with the permittivity of the solvent, hence the use of solvent mixtures with higher permittivities. The same experimental procedure was used for the depth probe using water and potassium chloride for conductivities up to 0.5 S m^{-1}.

Results and discussion

MEASUREMENT OF C_O FOR THE ELECTRODES USING CAPACITANCE AND RESISTANCE

Measuring and plotting the electrode resistance against the electrical conductivity of the solution proved to be the more successful method of obtaining the value of C_o. The resistance measured by the bridge and TDR were compared (Fig. 2) and found to be very similar over this range of resistance. Plots of $1/R$ *vs* EC proved linear with r^2 values better than 0.99. The values of C_o determined from the slopes for 50, 100 and 150 mm electrode lengths were, however, approximately 15% lower than the values derived from theory (Table 1).

The capacitance method proved to be a very simple method of obtaining C_o. The values of C_o for the 50 mm and 100 mm electrodes were found to be 74% and 63% of the theoretical values respectively (Table 1). The

Table 1. Electrode capacitance in air C_o ($g.\varepsilon_o.\ \varepsilon_{air}$) determined by theoretical analysis; measurement in ionic solutions and by measuring the electrode capacitance.

Eletrode capacitance in air C_o 50 mm		Electrode length/type 100 mm	150 mm	Depth probe	
Calculated value					
Theoretical in air	(pF)	0.66	1.32	1.99	–
Measured values					
Slope 1/R vs EC	(pF)	0.59	1.10	1.72	–
Capacitance	(pF)	0.49	0.83	–	3.90

measurement of capacitance of 1 pF and below was unsatisfactory as the bridge was close to the limit of its measuring range. Accurate measurement of such small capacitance becomes difficult as external factors, such as the capacitance of the connecting wires, begin to affect the measurement. Success using this method would require a more accurate measuring device with electrodes in a more controlled environment.

CALIBRATION OF SCIPS USING THE ALTERNATIVE VALUES OF C_O

The different values for C_o determined for 50 and 100 mm electrodes, displayed in Table 1, were used to calculate C_1 and inserted into Eqns (4) and (5). The air and water frequencies for each of the 10 SCIPs were used, along with each of the values of C_o and the corresponding values for C_2 and L, to produce predicted relationships between relative permittivity and oscillation frequency. The modelled relative permittivity was then determined from the probe frequency (F) in each dielectric by rearranging Eqn. (3) as Eqn. (9); the modelled permittivities are compared with the literature values (Lide, 1992) in Table 2.

$$\varepsilon_r = \frac{C_3 - 4.\pi^2.F^2.L.C_2.C_3 + C_2}{(4.\pi^2.F^2.L.C_3 - 1).C_o} \qquad (9)$$

The results using the values of C_o derived through measured capacitance were the least accurate, considerably overestimating permittivity in all cases, whilst the other two methods ($1/R$ *vs* EC and the theoretically calculated values of C_o) produced results in much closer agreement with values obtained from the literature. The use of the theoretically-determined value of C_o underestimated the relative permittivity in the acetone by about 2, but was more accurate in estimating the higher glycol permittivity. The resistance-measured value of C_o was more accurate for the acetone, but overestimated the relative permittivity of the glycol by just over 1. In moist soils, permittivities are generally in the range of 5–30. This work suggests that the most accurate permittivity determination can be made using a value of C_o estimated from the resistance across the electrodes. Individually calibrated probe electrodes may well offer even better results, but those presented here are more than comparable with permittivity measured by other methods.

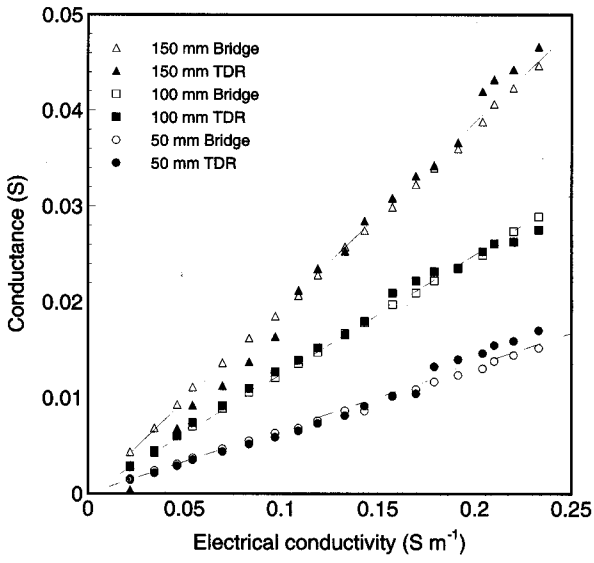

Fig. 2. *A comparison between electrode conductance measured by the bridge method and the time domain reflectometer.*

CALIBRATION OF THE EXPERIMENTAL SCIP AND DEPTH CAPACITANCE PROBE

The resistance-measured values of C_o (Table 2) were used to derive calibration relationships for the experimental SCIP with 50, 100 and 150 mm detachable electrodes. These results are plotted with the data determined from measurements in a number of different organic dielectrics (Fig. 3). Correlation of the actual permittivities with those predicted by the model resulted in r^2 values of 0.991, 0.998 (n=10) and 0.988 (n=7) for the 50, 100 and 150 mm electrodes respectively. This compares very favourably with the statistical model results of Dean (1994) and demonstrates that two measurements in air and water only can be used to calibrate a capacitance probe in terms of relative permittivity.

Table 2. Relative permittivities measured by 10 capacitance probes using values of C_o determined from theoretical calculation and measurement by capacitance and conductance *vs* solution electrical conductivity.

Organic liquid	Theoretical calculation 50 mm ($g.\varepsilon_o$ 0.66)	S.D.	Capacitance 50 mm ($g.\varepsilon_o$ 0.49)	S.D.	$1/R$ *vs* EC 50 mm ($g.\varepsilon_o$ 0.59)	S.D.
Chloroform (ε_r 4.81)	4.35	0.06	5.01	0.10	4.59	0.06
Acetone (ε_r 21.19)	18.94	0.37	21.78	0.43	19.96	0.38
Glycol (ε_r 38.69)	38.45	0.66	42.23	0.67	39.88	0.65
	100 mm ($g.\varepsilon_o$ 1.32)	S.D.	100 mm ($g.\varepsilon_o$ 0.83)	S.D.	100 mm ($g.\varepsilon_o$ 1.10)	S.D.
Chloroform (ε_r 4.81)	4.35	0.07	5.83	0.20	4.86	0.08
Acetone (ε_r 21.19)	18.69	0.46	24.68	1.14	20.82	0.47
Glycol (ε_r 38.69)	37.18	1.19	45.65	2.78	40.21	1.04

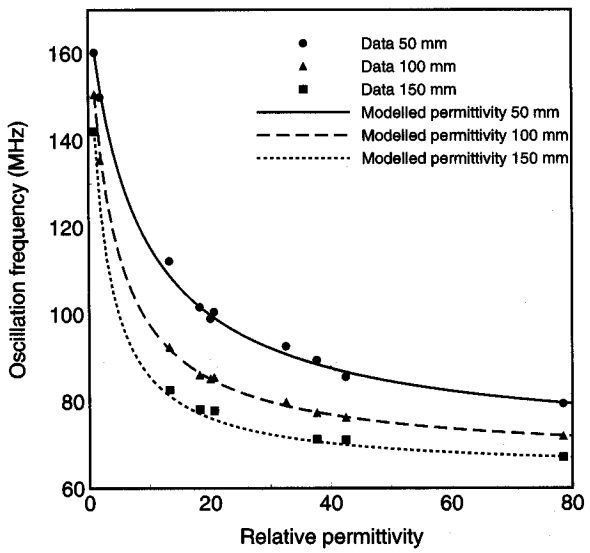

Fig. 3. *Modelled capacitance probe oscillation frequency response for 50, 100 and 150 mm electrodes. Data points are the average values for five measurements taken in each of the dielectric fluids.*

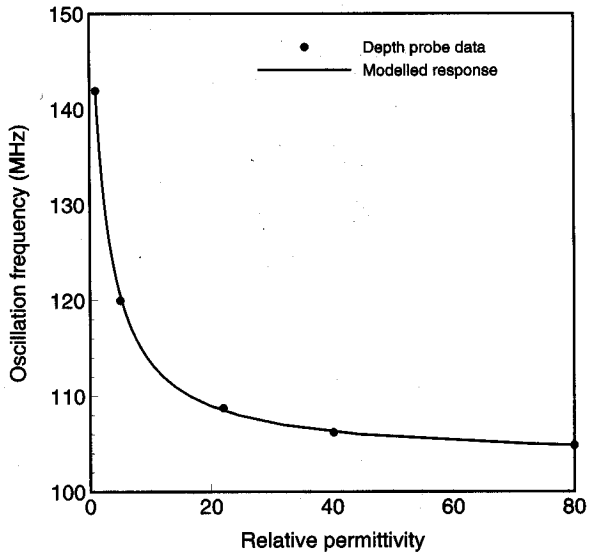

Fig. 4. *Modelled capacitance probe oscillation frequency response for the depth capacitance probe and data from a calibration in dielectric fluids.*

The resistance method could not be used to determine the value of C_o for the depth probe and it is difficult to calculate a theoretical value for this geometry. However, the capacitance can be measured directly, although it is still subject to some of the difficulties described earlier. C_o determined in this way was used in Eqn. (9) with the value of C_3 adjusted to 9.5 pF (Dean 1994); the model and data are compared in Fig. 4. The satisfactory agreement suggests that the procedure of calibrating in air and water can be applied equally well to the depth capacitance probe as to the SCIP.

THE IMPACT OF ELECTRICAL CONDUCTIVITY

Results in Figs. 5a and 5b show how increasing solution electrical conductivity increases the apparent permittivity (κ) measured by the SCIP (solid symbols). The apparent permittivity increases non-linearly as conductivity rises,

but this can be modelled physically. At low conductivity, the apparent capacitance of the electrodes is close to the true capacitance, but as conductivity increases, the apparent capacitance rises. In order to obtain an apparent permittivity (κ_c), corrected for the conductivity effects, the true capacitance can be calculated from Eqn. (7) and measured resistance across the electrodes. The open symbols in Figs. 5a and 5b show the corrected apparent permittivities (κ_c) calculated in this way. Figures 5a and 5b demonstrate that in solutions with high conductivity, ~ 0.2 S m^{-1}, the true real part of the permittivity may be overestimated by as much as 30 using the apparent permittivity without correction for the conductivity effect. The corrected apparent permittivity is much closer to the relative permittivity.

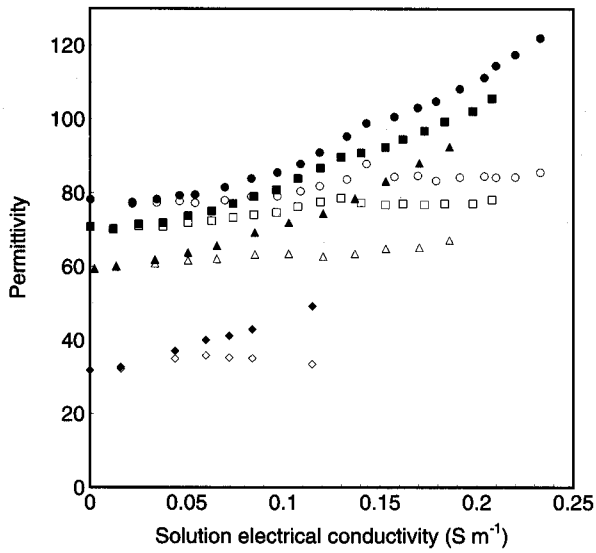

Fig. 5a. *The apparent permittivity (Solid shapes) and corrected apparent permittivity (Open shapes) determined from the capacitance probe frequency response for 50 mm electrodes. Water (circles), 20% methanol in water (squares), 42% methanol in water (triangles) and 64% propan-2-ol in water (diamonds).*

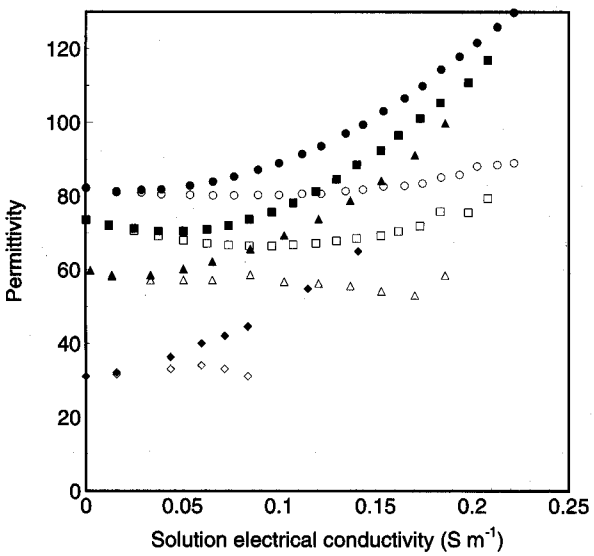

Fig. 5b. *The apparent permittivity (Solid shapes) and corrected apparent permittivity (Open shapes) determined from the capacitance probe frequency response for 100 mm electrodes. Water (circles), 20% methanol in water (squares), 42% methanol in water (triangles) and 64% propan-2-ol in water (diamonds).*

The same procedure was adopted for the depth probe and showed that the effect of a conducting medium is similar to, but less than, that experienced by the SCIPs. Figure 6 shows that conductivity still affects the probe frequency response even though there are no electrodes in contact with the conducting solution. The application of Eqn. (7) to determine the true capacitance was less successful for the depth probe using the same value of C_o as that determined from the electrode capacitance. To obtain the relative permittivity (open squares), the value of C_o, which determines the size of the resistance, had to be reduced to 1.9 pF. This may well be because the resistance acts across only a part of the electrode capacitance.

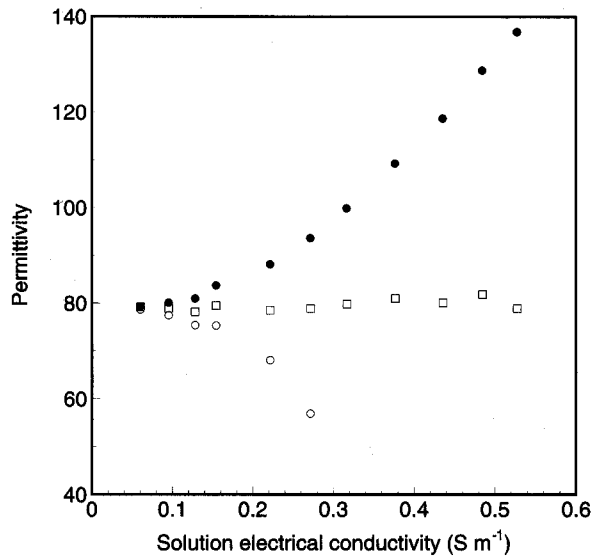

Fig. 6. *The apparent permittivity (solid circles) and corrected apparent permittivity calculated using Equation 6 (open circles) for the depth probe. Corrected apparent permittivity adjusted by changing the value of C_o (open squares).*

In an effort to reduce the effect of interference by the bulk soil electrical conductivity on the measurement of relative permittivity, capacitance probes have been developed to operate at progressively higher frequencies. However, high frequency measurements between 70 and 100 MHz (as used here) are still susceptible to the effects of the electrical conductivity of the soil solution. The effect of increasing soil solution conductivity is to damp the oscillatory circuit, reducing the oscillation frequency and so raising the apparent permittivity. Capacitance probes, therefore, overestimate water content in electrically conductive, wet soils as found by Mead *et al.* (1995). Fortunately, many soils are not electrically conducting

enough to cause problems; however, in some clay, saline or heavily fertilised soils, electrical conductivity can be within the range at which problems occur and so have a substantial impact on the estimation of water content using this method.

Conclusions

Relative permittivity can be determined accurately from the capacitance probe's oscillation frequency for bulk medium conductivity less than about 0.05 S m^{-1} in the case of the SCIP and less than 0.1 S m^{-1} for the depth probe. Each capacitance probe can be calibrated using two measurements, one in air and one in de-ionised water, avoiding the need for calibration in organic solvents. The conversion of frequency to permittivity means that instrument-independent calibrations may be established between soil permittivity and volumetric water content. Solution electrical conductivity has been demonstrated to increase the apparent permittivity measured by the probe. The effect can be modelled so that the true capacitance can be determined, allowing the corrected apparent permittivity to be obtained by correcting the apparent permittivity. Future work needs to investigate the effect of temperature on the conductivity and its subsequent effect on the determination of relative permittivity. Armed with this knowledge and a knowledge of the bulk electrical conductivity of the medium, the instrument can be used to measure permittivity in all soils, including those with high bulk soil electrical conductivity.

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